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THE SECONDARY STRUCTURES OF THE EASTERN PART OF THE BARABOO QUARTZITE RANGE, WISCONSIN

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INTRODUCTION

Despite the many valuable investigations on secondary structures from theoretical, experimental, and field viewpoints, practically no systematic attempt has been made to correlate secondary structures with stress strain relations which have given rise to major units of structure over large areas. The value of such investigations is being forced home, particularly in areas of poor exposure, where a few scattered details regarding the secondary structures are sometimes the only key to the major structure of industrially important areas.

PURPOSE AND SCOPE OF THE INVESTIGATION

This paper aims to set forth the relation of the joints and other secondary structures of the well-known and well-exposed eastern portion of the Baraboo quartzite range, to the stress strain relations which have developed the structural units of which the district is a whole or a part. On this basis the secondary structures of the district have been classified as those (1) related to the folding of the range, and (2) those not related to the folding of the range.

The[1] Baraboo quartzite district consists of an asymmetrical synclinical fold of pre-Cambrian formations, striking a little north of east and west, with a steep north limb and a gently dipping south limb. (See Fig. 2 of north-and-south section.) The succession from the base up is igneous rock, unconformity, quartzite, slate, iron formation, and dolomite. The only exposures are those of igneous rocks and quartzite, the latter making a prominent ridge encircling the district. The quartzite ridge of the north limb is known as the North Range, while that of the south limb is called the South Range.

Several months were spent in the field during 1905–6 in making several thousand observations on dips and strikes of beds and secondary structures, in an area comprising 5 square miles in the vicinity of Devil's Lake and the Lower Baraboo Narrows. Since then the problem has been reviewed annually by the writer, both in the field and in the office. Both data and results have received the criticism of C. K. Leith, to whom the writer is indebted.

SECONDARY STRUCTURES RELATED TO THE FOLDING OF THE RANGE

The secondary structures in the pre-Cambrian series of the Baraboo quartzite range consist of (1) closed, interrupted joints parallel to the bedding; (2) strike joints which intersect one or more beds and offset between the beds, and constitute a series of overthrust faults of minute throw; (3) strike cleavage both parallel and diagonal to the bedding.

The abundance of the joints related to the folding is dependent upon the inclination of the beds, the distance from the contact of formations, and the strength of the beds. They are more abundant where the strata are highly tilted, than where their dip is nearly horizontal. Thus in the quartzite of the South Range, having a dip of from 5–20 degrees north and striking N. 65–75 degrees east, only about 20 per cent. of the total number of joints are related to the folding; while on the North Range, where the quartzite strikes E.–W. and is vertical or nearly vertical in dip, 40 per cent. or more of the joints are connected with the folding, and of these, the joints parallel to the bedding are the more important. The diagonal strike joints of the North Range are nearly horizontal, owing to the vertical attitude of the beds.

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[1] Samuel Weidman, "Baraboo Iron Bearing District," *Wisconsin Geological and Natural History Survey, Bulletin No. 13*, 1904.

The effect which proximity to a contact has upon the abundance of joints related to the folding is well illustrated on the South Range near Devil's Nose, where the quartzite comes in contact with the granite porphyry to the south. At this place, both bedding and strike joints are so closely spaced as to break the quartzite into a rubble. Away from this contact, the zone of intense fracturing rapidly disappears.

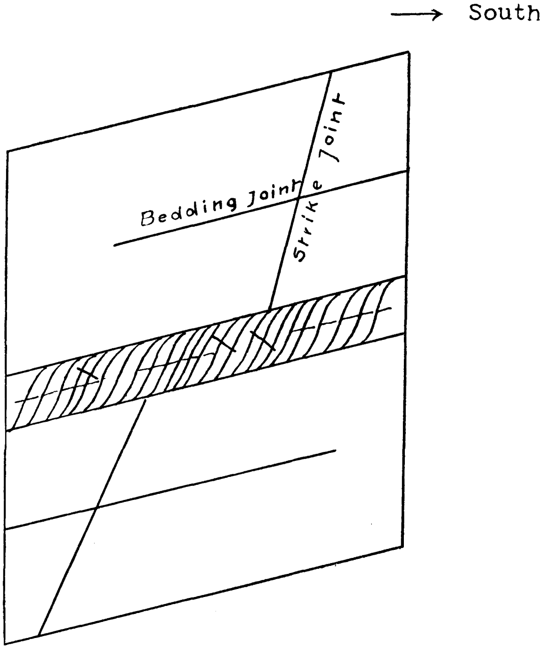

FIG. 1.—Vertical section, normal to the strike on the South Range, showing the relation of the joints connected with the folding in weak, thin beds interstratified with thick, strong beds.

Strong beds have fewer joints related to the folding than weak beds. Throughout the quartzite formation, weak, thin beds of slaty quartzite are intercalated between massive, strong beds of quartzite. Near the site of the old Cliff House on the east bluff at Devil's Lake, there are two such weak beds, each about a halffoot in thickness, separated by a thick bed of quartzite. Both bedding and diagonal strike joints are present in these beds. The beds strike N. 65 E., and dip 20 degrees north. The diagonal strike fractures are closely spaced *ʃ*-shaped fractures, which are nearly parallel to the bedding plane near the upper and lower surfaces of the bed, while at the center of the bed their dip is 50 degrees north. Some of these *ʃ*-shaped diagonal strike joints are connected with north-dipping diagonal strike joints in the strong quartzite beds. Another set of diagonal strike joints intersects the *ʃ*-shaped set. Fig. 1 shows the relation of the joints connected with the folding in thin, weak beds interstratified with strong, thick beds.

The igneous rocks both on the North and the South Range have joints related to the folding of the range. These joints strike parallel to the strike of the quartzite formation and are vertical or nearly vertical closed joints.

Locally intense dynamic activity accompanying the folding of the range has deformed the formations by flowage, resulting in the development of a schist. On the North Range, at the Lower Baraboo Narrows, in a zone about one hundred feet wide following the contact of the quartzite and the ryolite to the north, the ryolite and some of the quartzite have been rendered schistose. The strike of the cleavage conforms to the strike of the bedding of the quartzite. Its dip is vertical or nearly vertical in the quartzite. In the ryolite it varies from vertical to 65 degrees north.

SECONDARY STRUCTURES NOT RELATED TO THE FOLDING OF THE RANGE

The joints which are most conspicuous in the Baraboo quartzite formation, about 80 per cent. of the joints of the South Range, and approximately 60 per cent. of the joints of the North Range are not related to the folding of the range. Their strike and dip relations differ radically from the joints and secondary structures which are connected with the folding in that their strike and dip relations are independent of the strike and dip relations of the quartzite formation. These independent joints usually occur in sets at right angles to each other. They have considerable continuity both along the strike and the dip, and stand out as gaping, open, vertical, or nearly vertical fissures. On the South Range, the majority of these independent joints, about 60 per cent. of the total number of joints, strike N. 60 E. and N. 30 W. Nearly 20 per cent. strike N. 20–30 W., and the remainder strike in various other directions of the compass. On the North Range, the principal directions of rupture independent of the fold are N. 30–40 E., and N. 30–40 W., and N.–S.

It has been found that some of the joints unrelated to the folding are connected with deformation of the Cambrian. Thus the predominant directions of jointing in the Cambrian of the eastern end of the quartzite range is N. 60 E. and N. 30 W., which is the predominant direction of rupture of the quartzite on the South Range. This does not preclude the possibility that this set of fissures existed in the quartzite before the deformation of the Cambrian. It has been observed repeatedly that N. 60 E., N. 30 W., N. 10 E., N. 30 E., N. 35 E., N. 50 E., N. 20 W., N. 25 W., N. 35 W., N. 60 W., N. 70 W., N. 80 W. joints are continuous through both Cambrian sandstone and pre-Cambrian quartzite. On the other hand there is abundant evidence that many joints independent of the fold existed in the quartzite before the Cambrian was deposited, since (1) these continuous vertical joints are more prominent in the quartzite than in the Cambrian; (2) the quartzite conglomerate bowlders at the base of the Cambrian are dissected by a diversity of joints, some of them cemented with quartz, many of which could not have been related to the folding, or have developed by processes connected either with the deposition or the deformation of the Cambrian; (3) the Cambrian sandstone has been deposited in wide gaping fissures of the quartzite whose directions are independent of dip and strike relations of the quartzite. Thus at Devil's Lake where the quartzite strikes N. 65–75 E., and dips from 5–25 N., a vertical fissure several feet in width, striking N. 25 W., is filled with Cambrian sandstone.

Among the secondary structures independent of the fold are a few small, vertical shear zones[1] in the quartzite on the east bluff of Devil's Lake. The largest of these strikes N. 85 W. Since the south wall of this fault is more intensely shattered than the north wall, and shows a drag toward the south, it is concluded that the south wall has dropped with reference to the north wall. The amount of lateral or vertical displacement is not known, but these movements have very likely been small since the lateral extension of the shear zone appears to be very limited.

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[1] See illustration on p. 17, Rollin D. Salisbury, "The Geography of the Region about Devil's Lake and the Dalles of the Wisconsin," *Bulletin No. 5, Wisconsin Geological and Natural History Survey.*

RÉSUMÉ OF THE SECONDARY STRUCTURES

The cleavage and a minority of the joints of the pre-Cambrian rocks exposed on the eastern end of the Baraboo quartzite range are related to the folding of the range. On the South Range, about 20 per cent. of the joints, and on the North Range, about 40 per cent. are related to the folding.

Many of the joints of the pre-Cambrian are independent of the folding, having been developed in part before the deposition of the Cambrian, and in part after the deposition of the Cambrian. About 80 per cent. of the joints of the South Range and 60 per cent. of those of the North Range are unrelated to the folding.

THE MECHANICS OF THE SECONDARY STRUCTURES OF THE EASTERN PART OF THE BARABOO QUARTZITE RANGE

It is evident from the description of the secondary structures of the Baraboo quartzite range that there are two distinct types of joints present. The joints of the predominant type, comprising about 80 per cent. of the joints of the South Range, and about 60 per cent. of the joints of the North Range, are independent in their strike, dip, and space relations of the quartzite formation. They were not produced by the folding of the range, but by later deformations. Another type of joints, comprising about 20 per cent. of the joints of the South Range, and 40 per cent. of the joints of the North Range, are connected with the folding of the range. They are the vertical and north-dipping discontinuous, diagonal strike joints, and the bedding joints of the South Range, and the bedding joints and the nearly horizontal strike joints of the North Range. The two types will be given separate attention.

THE SECONDARY STRUCTURES PRODUCED BY THE FOLDING OF THE RANGE

The folding of the quartzite formation was accomplished by slipping between the beds, by fracturing, and by the flowing of the beds.

These movements were in the direction of the anticlinal axis of the fold for an upper bed with reference to a lower bed, and in the direction of the synclinal axis for a lower bed with respect to an upper bed. More deformation took place in weak beds than in strong beds; more in highly tilted beds than in slightly tilted beds. Other factors also influenced the movement. For instance, a large amount of readjustment took place at the contact of the quartzite and the underlying igneous rocks. It may be that this was due to the absence of easy planes of slipping in the massive igneous rocks and that consequently a large part of the required amount of movement took place at the contact of the two formations. Fig. 2 represents a diagrammatic north-to-south section of the quartzite formation. The arrows indicate the direction of movement in the beds in the process of folding. *A* and *B* represent sections of cubes in the beds before deformation. After deformation, the cubes will be deformed into parallelopipeds, and the sections *A* and *B* will be deformed into parallelograms. Spheres inscribed in the original cubes are deformed into ellipsoids called the strain ellipsoids. Fig. 3 represents *A* of Fig. 2, a vertical section of a cube normal to the strike, and the parallelogram resulting from the deformation of *A*; the circle inscribed in *A*, and the resulting ellipse of strain. Fig. 4 represents a similar section on the North Range where the bedding is vertical. The arrows indicate the direction of slipping between the beds.

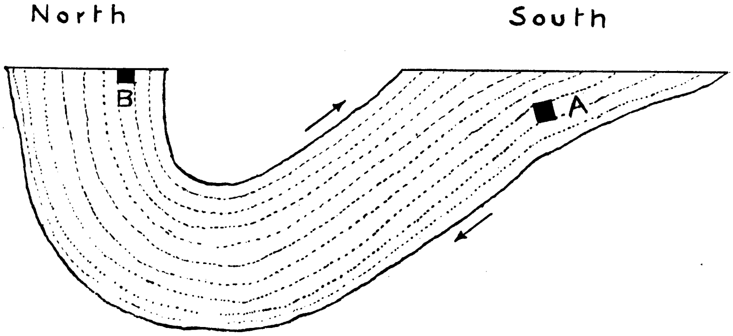

FIG. 2.—Diagrammatic north-to-south section of the quartzite formation. Scale of cross-section: $\frac{3}{4}$ inch = 1 mile. *A* and *B* represent sections of cubes in the beds before deformation.

The massive quartzite beds and the massive igneous rocks were deformed largely under conditions of fracture, excepting at the contact of the two formations where some of the deformation was accomplished by flow. Those rocks which were deformed under conditions of fracture ruptured as soon as the stresses exceeded the ultimate strength of the rocks. According to the best mechanical analysis, rupture which results from compression takes place along the planes of no distortion or constant area, since these are the planes of maximum tangential stress. In Figs. 3 and 4 they are represented by *XY* and *LM*. It is evident that *LM* is equivalent to the bedding joints, and *XY* is the vertical, or north-dipping strike fracture, diagonal to the bedding of the South Range, or the nearly horizontal strike fracture of the North Range, where the beds are steeply inclined. The strike fractures constitute a series of overthrust faults of minute throw, which approximately bisect the angle between the longest axis of the strain ellipsoid and a normal to the bed. The initial angle between the longest axis of the strain ellipsoid and a normal to the bed is 45 degrees. The rotation of the longest axis of the strain ellipsoid beyond the initial 45-degree position depends upon the amount of internal flow coincident in direction with the movement between the beds. Since more internal flow takes place in weak beds than in strong beds other conditions being the same, the strain ellipsoids are rotated

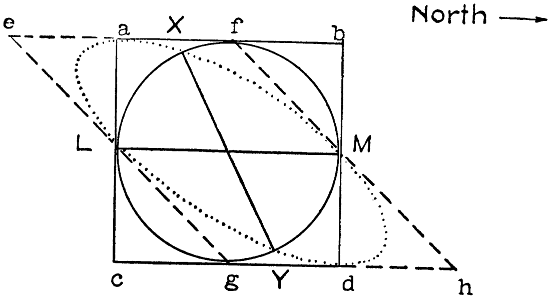

FIG. 3.—*abcd* represents *A* of Fig. 2; *efgh* represents the parallelogram of strain resulting from deformation; the circle inscribed in *A* has been deformed into an ellipse. *XY* and *LM* are the planes of no distortion or the planes of maximum tangential stress, and of rupture.

more in weak beds than in strong beds, and hence the diagonal strike fractures are more nearly parallel to the bedding in weak beds than in strong beds. This principle accounts for the ʃ-shaped fractures in the shaly layers at Devil's Lake, previously described. Near the upper and the lower surfaces of these weak beds, where internal adjustment was greatest, these fractures are more nearly parallel to the bedding than in the center of the beds, where internal adjustment was least. The stretching of the beds parallel to the longest axis of the strain ellipsoid causes tension fractures to develop normal to the direction of maximum elongation. See diagonal strike fractures which intersect the ʃ-shaped strike fractures of Fig. 1.

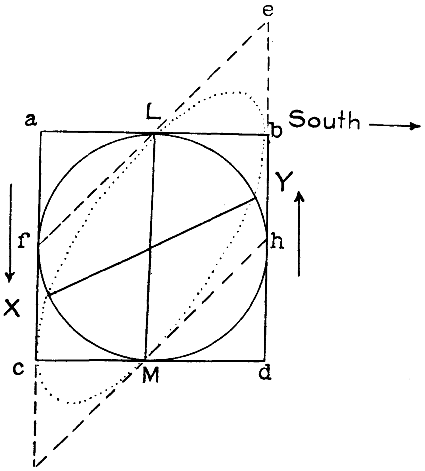

FIG. 4.—*abcd* represents *B* of Fig. 2; *efgh* represents the parallelogram of strain resulting from the deformation of *abcd*. *XY* and *LM* are the intersections of the circle inscribed in *abcd* and the strain ellipse resulting from the deformation of the circle. *XY* and *LM* are the directions of maximum tangential stress, and of rupture.

The development of bedding and diagonal strike shearing joints by the folding on the north limb of the Baraboo syncline is illustrated by Chamberlin and Salisbury in *Geology*, Vol. I, p. 445, Fig. 367. The bed on the left of Fig. 367 is a weak, shaly bed stratigraphically beneath the stronger quartzite bed to the right. In the weak bed the diagonal strike fractures are closely spaced, while both bedding and nearly horizontal, diagonal strike fractures, rather widely spaced, are visible in the stronger bed. The movement of the stronger bed has been upward with reference to the weaker bed.

The preceding analysis seems to account for all the fractures which show by their strike, dip, and other relations that they are related to the folding of the range. It is to be noted that these fractures are the result of compression rather than tension. Theoretically, it is possible that tension may have caused a set of vertical, gaping strike joints especially on the crest and trough of the fold. It is difficult to determine what part of the strike and dip joints are of this origin, but most of this class have been connected by observation with the compression joints produced by the folding of the range, and thus far no definite evidence of tension joints related to the folding has been found.

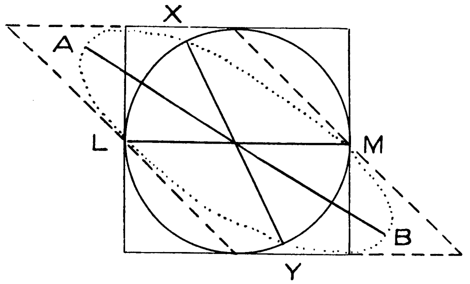

FIG. 5.—*AB*, the longest axis of the strain ellipsoid, is the direction of cleavage in a rock deformed by flow. *XY* and *LM* are the directions of rupture in a rock deformed under conditions of fracture.

Wherever deformation was accomplished largely by flow, cleavage resulted. Cleavage is the capacity of a rock to part along parallel surfaces which are determined by the orientation of the mineral particles parallel to the longer axis of the strain ellipsoid. Fig. 5 shows the strain ellipsoid and the direction of cleavage parallel to the longest axis *AB* of the strain ellipsoid as compared with the directions of maximum tangential stress or rupture *XY* and *LM*. The degree of rotation of the strain ellipsoid, and hence the inclination of the cleavage with respect to the bedding, depends upon the amount of flow. On the North Range, at the contact of the igneous rocks and the quartzite, the plane of cleavage is nearly parallel to the bedding of the quartzite. Farther to the north in the igneous rocks where flowage was less intense, the dip of the cleavage is diagonal to the inclination of the quartzite beds. The cleavage, in the granite porphyry on the South Range at Devil's Nose, is inclined to the north at a steeper angle than the overlying quartzite beds.

THE SECONDARY STRUCTURES INDEPENDENT OF THE FOLD

It is believed that the joints which are independent of the Baraboo syncline are due to tension rather than compression, since they lack strike and dip relations but are usually vertical, open, and occur in approximately rectangular sets whereas, if they were due to compression, they would occur as closed, inclined shearing joints, striking more nearly in one direction.

If the joints, which are independent of the syncline, are due to tension, then the most probable source of tensile stresses would be complex folding under conditions of moderate load. Under such conditions folding will produce rectangular sets of strike and dip joints normal to the direction of tensile stress.

From the description of the secondary structures, it follows that the Baraboo quartzite was subjected to at least one deformation after the folding and before the Cambrian was deposited, and at least one deformation after the deposition of the Cambrian. It seems that one of the principal directions of rupture caused by the deformation following the folding was N. 20–3c W., and therefore it is possible that this was one of the axial directions of this deformation. The directions of maximum rupture in the Cambrian are N. 60 E. and N. 30 W., and therefore assuming that these joints are due to tension caused by complex folding, the axes of the Cambrian fold are approximately N. 60 E., and N. 30 W., in the district. The intermediate systems may have originated with the preceding systems of independent joints, or they may have developed through other stresses.

CONCLUSION

About 20 per cent. of the joints of the South Range, and 40 per cent. of the joints of the North Range are compressive shearing joints developed in planes parallel to the bedding, and in planes parallel to the strike and diagonal to the bedding by strains developed during the formation of the Baraboo syncline. A part of the joints so classed may be due to tension, but there is no direct evidence of this.

The remaining joints, constituting about 80 per cent. of the joints of the South Range, and 60 per cent. of the joints of the North Range, are obviously independent of the folding of the range, having no relation to the attitude of the bedding. Their origin is uncertain, but a large proportion of them are probably tension joints controlled by larger units of structure than Baraboo Range.

The cleavage locally developed in the rocks of the Baraboo syncline has been correlated with the folding of the range.

The results of this investigation emphasize a principle which has not often received adequate attention, that the secondary structures are parts of larger structures, that these in turn are parts of still larger structures, and that therefore the secondary structures may be the key to the major structure. Description of joints, fractures, cleavage, and faults, as so many isolated details, has value in the interpretation of earth history, only when it leads to the correlation of these structures with the major structures of a district.